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ULTRA-SMOOTH DRY ETCHING OF GaAs USING A HYDROGEN PLASMA PRETREATMENT

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ABSTRACT

We have attained extremely smooth etched surfaces on GaAs using a hydrogen plasma pretreatment before etching. The resultant morphology exhibits smooth surfaces since the etching proceeds uniformly through the GaAs without micromasking effects arising from a nonuniform surface oxide. We report the effects of hydrogen plasma treatments before RIE of GaAs in two different reactors using a $SiCl_4$ plasma. Optimization of H_2 plasma pretreatments has produced improvements in RMS roughness greater than 1 order of magnitude (22.4 to 1.51 nm).

INTRODUCTION

Typically at the start of reactive ion etching (RIE), there is an initiation period during which no GaAs etching occurs. Only after penetration of the native oxides on the surface will etching begin. Moreover, even with a short initiation period, micromasking effects due to nonuniform oxide thickness can lead to a roughening of the etched surface. Therefore, removing the native oxide before RIE should lead to greater process control and uniformity, as well as insuring a smooth etched surface necessary for epitaxial regrowth or uniform metal contacts.

Hydrogen plasmas have been previously shown to selectively remove native oxides from GaAs [1-3]. We have used a hydrogen plasma treatment before dry etching to remove the surface oxides. We discuss the effects of a hydrogen plasma pretreatment before etching with a $SiCl_4$ plasma; the GaAs surface roughness is characterized using scanning electron microscopy and atomic force microscopy.

EXPERIMENTAL

The GaAs wafers used in this study are two inch diameter semi-insulating substrates. The photoresist etch mask is approximately 1.4 µm thick AZ-5214 with circular mesa features ranging in diameter from 4 to 32 µm on 250 µm pitch. The samples are 1 cm^2 to minimize loading effects. The etched surface morphology is quantified using a Digital Instruments atomic force microscope (AFM) operating in air in contact mode. The data is reported as RMS surface roughness which represents the standard deviation of the roughness values within a 2500 μm^2 area.

RIE etches were performed at Sandia National Laboratories, Albuquerque (SNL) and AT&T Bell Laboratories, Murray Hill (AT&T) to evaluate the effect of a H_2 plasma pretreatment on GaAs etching. The SNL RIE reactor is a non-load-locked 13.56 MHz rf-powered parallel plate Semi-Group RIE system. The lower electrode is 30.5 cm in diameter with an interelectrode spacing of approximately 3.8 cm. Samples were also etched at AT&T in a 13.56 MHz rf-powered parallel plate Oxford PlasmaLab RIE system with a lower electrode diameter of 16.8 cm and separation of 5.0 cm. The AT&T RIE chamber was enclosed with a glove box filled with dry N_2 to reduce H_20 in the system. In both reactors samples were attached to a quartz plate, which completely covered the lower electrode, with thermal paste to ensure good thermal conduction. Immediately before loading, the samples were subjected to a 30 sec NH_4OH:DI H_20 (1:20) rinse.

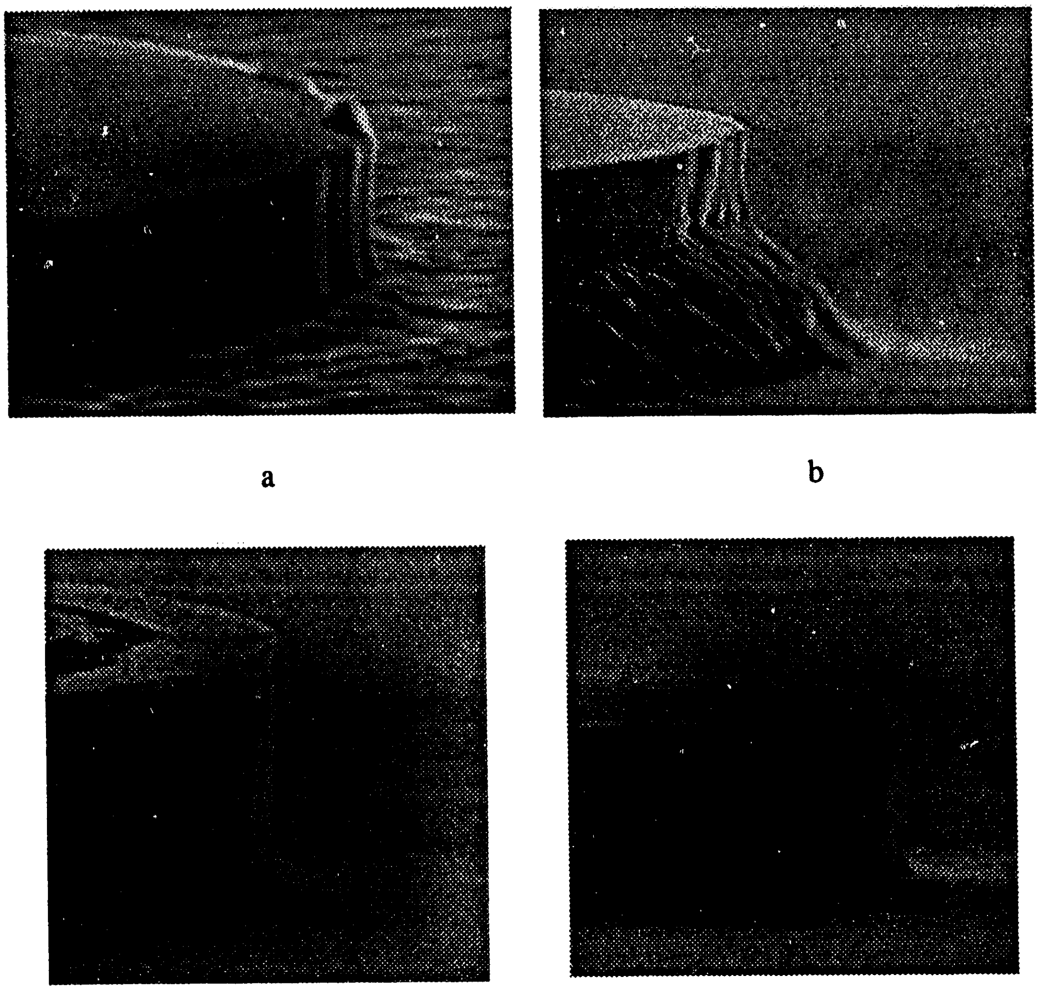
Nominally matching plasma conditions between the two RIE systems did not yield similar etch results; therefore power densities were optimized for each reactor while the pressures and flow rates were held constant for both the H_2 and $SiCl_4$ plasmas. In the SNL RIE, the H_2 plasmas were run at 335 mW/cm^2 and the $SiCl_4$ plasma etches were run at 80 mW/cm^2. The AT&T H_2 plasma was optimized at 320 mW/cm^2 and the $SiCl_4$ plasma was run at 160 mW/cm^2. Temperature was maintained at 0°C and 50°C in the SNL reactor and -16°C and 50°C in the AT&T reactor. All pretreatment and etch experiments were run at 20 sccm H_2 flow rate at a pressure of 20 mTorr and 10 sccm $SiCl_4$ flow rate at a pressure of 5 mTorr.

RESULTS AND DISCUSSION

A. Etch Rates and Profiles

The GaAs etch rates for the SNL reactor are 250 nm/min at 0°C and 300 nm/min at 50°C. The higher etch rate at 50°C may be due to increased volatility of the etch products and improved H_2O removal from the chamber at higher temperatures. In the AT&T reactor the etch rates are 110 nm/min at -16°C and 135 nm/min at 50°C. Comparing the SNL and AT&T etch rate data shows a much faster etch in the SNL reactor. This is surprising since the SNL reactor is run at one-half the plasma power density of the AT&T reactor and may be attributed to differences between the two reactors.

GaAs features etched in the SNL reactor are anisotropic independent of temperature and of exposure to the H_2 plasma pretreatment (Figure 1a). However, GaAs etching in the AT&T reactor shows a significant widening at the base of the mesa feature at 50°C and no H_2 pretreatment (Figure 1b). This profile may be due to reflow of resist at higher temperature and higher incident power density from the plasma since the AT&T plasma power density is a factor of 2 greater than that used in the SNL reactor. Also, since the GaAs etch rate in the AT&T reactor is almost a factor of 3 slower than that in the SNL reactor, longer exposure times are necessary to etch to similar depths and may change the resist profile. The profile appears much more anisotropic with a H_2 plasma pretreatment suggesting the H_2 plasma interacts with the resist to enhance the anisotropy of the GaAs etch (Figure 1c). Low temperature (-16°C) etching in the AT&T reactor is highly anisotropic independent of the H_2 pretreatment (Figure 1d) presumably due to the lack of resist reflow at the lower temperature.



a

b

c

d

Figure 1: SEM micrographs of GaAs etched in $SiCl_4$ plasma (a) in the SNL reactor at 50°C without H_2 plasma exposure (0.75 µm deep), (b) in the AT&T reactor at 50°C without H_2 exposure (1.7 µm deep), (c) in the AT&T reactor at 50°C with 2 minutes of H_2 plasma exposure (1.1 µm deep), and (d) in the AT&T reactor at -16°C without H_2 exposure (1.0 µm deep).

B. Surface Morphology

AFM images for surfaces etched in $SiCl_4$ are taken and analyzed for RMS roughness. The SNL and AT&T RMS data is shown in Figures 2 and 3, respectively. A patterned, unetched sample has an RMS roughness value of 0.628 nm. In Figure 2, the GaAs samples etched at SNL at 0°C and 50°C show a decrease in RMS roughness as the H_2 exposure is increased to 4 minutes; a slight increase in RMS roughness occurs as the exposure time is increased to 10 minutes. At both 0°C and 50°C, the optimum surface morphology occurs after 4 minutes of H_2 pretreatment. The rough etched surface observed at 0°C and 1 minute H_2 exposure is probably due to incomplete removal of the native oxide, which causes micromasking effects during the $SiCl_4$ plasma etch. As the H_2 exposure time is increased, the oxide is more uniformly removed

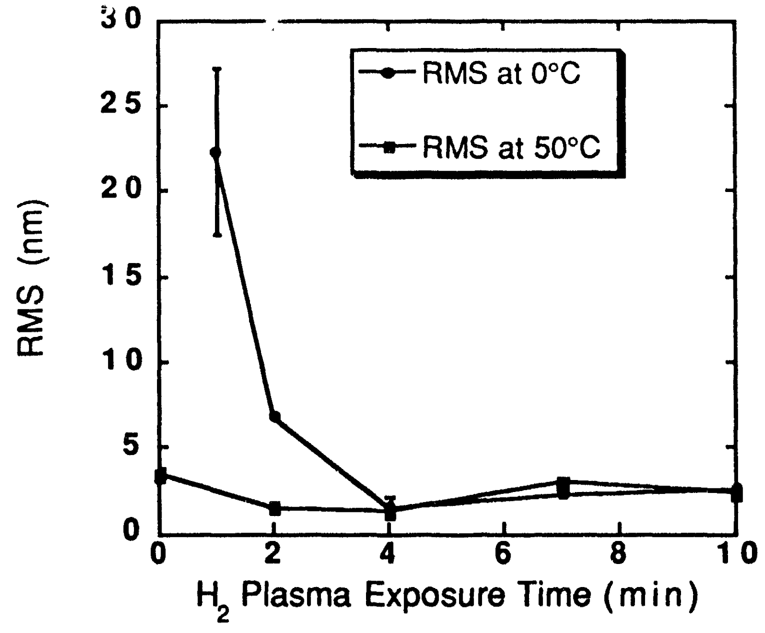


Figure 2: RMS roughness as a function of H_2 plasma exposure time for samples etched in the SNL reactor at 0°C and 50°C.

and the RMS roughness improves from 22.4 nm at 1 minute H_2 exposure to 1.51 nm at 4 minutes H_2 exposure. Without exposure to the H_2 plasma at 0°C, GaAs etching does not occur in a 80 mW/cm^2 $SiCl_4$ plasma. However, GaAs etching is achieved when the power density is increased to 160 mW/cm^2 with an RMS roughness of 1.34 nm. This implies that at 80 mW/cm^2, the $SiCl_4$ plasma cannot penetrate the native oxide and initiate GaAs etching. At 50°C, the surface morphologies are relatively smooth regardless of the H_2 exposure time; however, the RMS roughness improves from 3.47 nm without H_2 exposure to 1.29 nm with 4 minutes H_2 exposure. We also note that the GaAs etches at 50°C without exposure to a H_2 plasma. The elevated temperatures may enhance the volatility of the etch products as well as H_2O removal from the chamber, thereby uniformly removing the native oxide during the $SiCl_4$ etch.

A similar trend is observed for GaAs etching at AT&T. In Figure 3, we observe an improvement in the etched surface morphology with the addition of the H_2 plasma pretreatment. At both -16°C and 50°C the optimum surface morphology is observed after a 2 minute H_2 exposure. Low temperature etching yields very smooth GaAs surfaces independent of the H_2 pretreatment. The surface morphology improves slightly from 0.986 nm without H_2 exposure to 0.907 nm with a 2 minute exposure. Comparing the low temperature etching at SNL and AT&T, we find significant improvement of the surface morphology in the AT&T reactor at low H_2 plasma exposures. We believe the smoother surfaces obtained in the AT&T etches are due to the effect of the dry N_2 glove box which lowers the H_2O concentration in the chamber and minimizes its effect on removal of the native oxide and GaAs etching. However, the surface morphologies become similar as the H_2 exposure is increased to 4 minutes. The roughest surface morphology in the AT&T reactor occurs without H_2 exposure at 50°C. The RMS roughness data is more than an order of magnitude greater than that for the low temperature AT&T etch without H_2 exposure. The smoother surface morphology at low temperature may be due to a lower chemical component of the etch mechanism at -16°C. Comparing the high temperature etching at SNL and AT&T, we see the AT&T RMS roughness is three times greater than the SNL roughness without H_2

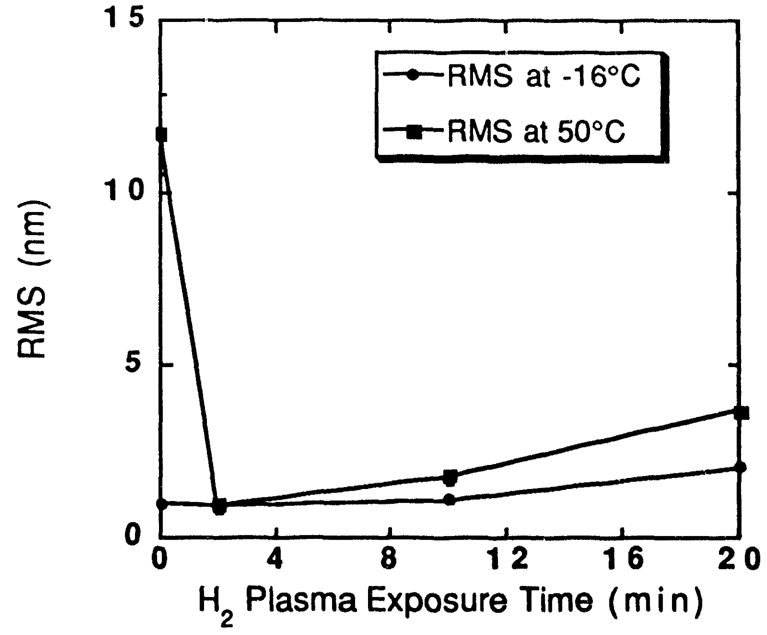


Figure 3: RMS roughness as a function of H_2 plasma exposure time for samples etched in the AT&T reactor at -16°C and 50°C.

exposure. Since the effect of the glove box is minimized at high temperatures due to lower H_2O concentrations in the chamber, the higher power density in the AT&T etch may cause the rougher surfaces. Under all etch conditions studied, the surface morphology seen in the two reactors tends to converge as the H_2 exposure is increased.

Several trends can be deduced from this study. First, transferring processes from one reactor to another is difficult. We have observed significant variations in the etch characteristics using "identical" processes in the two reactors. Many of these variations can be attributed to the fact that the AT&T reactor incorporates a dry N_2 glove box which minimizes the H_2O concentration in the chamber and permits more uniform removal of the native oxide and smooth GaAs etching. Additionally, differences in interelectrode spacing may effect the ion bombardment energies in the plasma and cause differences in etch characteristics. Etch variations may also be due to differences in thermal contact of the samples to the lower electrode. Second, under all conditions studied we have observed an improvement in the GaAs etched surface morphology with the addition of a H_2 plasma pretreatment. The surface morphologies are similar independent of reactor or temperature as the H_2 exposure time is optimized (2 to 4 minutes in this study). We believe that the slight increase in surface roughness with increasing H_2 exposure is due to an interaction between the H_2 and the photomask leading to micromasking effects. Also, changing the power density of the H_2 plasma from 335 to 165 mW/cm^2 has virtually no effect on the surface morphology of the GaAs etched surfaces suggesting a robust process window for the H_2 pretreatment.

CONCLUSIONS

H_2 pretreatment for 2 to 4 minutes yields a smoother etch morphology and reproducible etch characteristics for $SiCl_4$ etching of GaAs in two different RIE reactors. Attempts to transfer processes between the two different chambers was not straightforward. However, a H_2 plasma pretreatment results in improved surface morphology, as quantified with AFM, in both reactors. The H_2 plasma selectively removes the native oxide on GaAs before RIE, resulting in an etch morphology which exhibits significantly less surface roughness since the etching can proceed uniformly through the GaAs.

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